

degree of freedom, and hence rotate about both the principal axis and a vertical axis, we need consider only those angles so oriented as to give minimum deviation. The corresponding images are obtained by assigning a series of arbitrary values to θ , and giving the deviation its minimum value for each one, in the appropriate trigonometrical formulas; the resulting loci are known as the tangent arcs to the 22° halo, and are examples of arcs produced by the combined effects of minimum deviation (not minimum minimorum) and predominant orientation.

To calculate the halos which will be produced by crystals deprived of two degrees of freedom, and hence rotating only about a vertical axis, we need consider only the two equilibrium positions. The rare Parry arc above the 22° halo is due to light which is incident on the top faces of crystals which have two lateral faces horizontal; this arc is an example of a halo produced by a predominant orientation alone. A more common example is the circumzenithal arc, produced by 90° refracting angles with one face horizontal and the other vertical; in this case the general formulas show that the circumzenithal arc is simply a circle parallel to the horizon. It often occurs alone, and is the most brilliantly colored of all halos; in spite of its position in the sky it frequently is reported as a rainbow. The ordinary 22° sundogs are likewise due to crystals

which have only one degree of freedom, but the principal plane of the refracting angle (60°) is horizontal in this case; it is to be noted that the sundogs are *outside* the corresponding halo—except when the luminary is on the horizon. The visible portion of the locus is ordinarily that at and near minimum deviation but is not at the minimum minimorum.

Reflection from vertical crystal faces rotating about a vertical axis produces the white parhelic circle, passing through the sun parallel to the horizon. Finally, an interesting example in which total internal reflection is involved may be mentioned: Light which at a high altitude of the sun falls upon the two upper sloping faces of hexagonal columnar crystals that have two lateral faces horizontal, and emerges from the lower horizontal face after internal reflection by a vertical plane base, the crystals being randomly oriented in azimuth, produces the so-called Lower Oblique Arcs of the Antheion, which are among the rarely observed phenomena.⁹

The following sections¹⁰ will present a systematic arrangement of formulas from which the various arcs mentioned above, as well as all others that can be produced in the different possible cases, may be computed.

⁹ Edgar W. Woolard, On the Lower Oblique Arcs of the Antheion, *MON. WEATHER REV.*, 50: 537-539, 1922.

¹⁰ To be published in later issues of the *REVIEW*.

WIND AND MINIMUM TEMPERATURE IN THE REDLANDS, CALIFORNIA, FRUIT-FROST DISTRICT

By JACK JANOFSKY

[Weather Bureau, Pomona, Calif., October 1936]

Fruit-frost work on the Pacific coast began in 1917. Starting with 2 widely separated stations, the service has since grown to include 18 winter and spring districts. The forecasting difficulties encountered in two different districts are never wholly alike, varying with the season and geographical location. When positive signs point to the development of ocean cloudiness, radiation fog, or wind during the night, no major forecasting difficulties are presented; but when indications are less definite, forecasting minimum temperatures becomes exceedingly difficult.

In the Redlands, Calif. district, wind is the important consideration; because no other phenomenon can there influence temperature forecasts so readily, it is especially deserving of critical treatment. The paper which follows presents a study of wind in the Redlands fruit-frost district, but the methods used should yield consistent results elsewhere.

The Redlands fruit-frost district lies in the northern extremity of the Great Valley of southern California, one of the richest citrus-growing centers in the world. Resembling a right triangle in shape, with the San Bernardino Mountain Range on the north as hypotenuse and the foothills of the San Jacinto Mountain Range on the south as base, the district is roughly 110 square miles in area. The foothill ranges converge in the east, with Crafton Hills, 3,540 feet high, closing the valley; but to the right and left rear are the San Gorgonia and San Jacinto peaks approximately 11,000 feet above sea level. The district opens in the west and merges 20 miles away with the flatter Great Valley to include the communities of Fontana and Bloomington as the western limits. The smooth valley floor slopes gently from the foothill areas and drains radially to the point of lowest elevation 7 miles southeast of Fontana, near Colton, about 950 feet above sea level. Elevation contours run in a general north-south direction in the east near Redlands, and an east-

west direction near Fontana. A representative slope for the valley floor would be 75 feet per mile, but on approaching the foothills the slope gradient steepens rapidly.

Despite the small size of the district, forecasting minimum temperatures is complicated by a formidable wind problem. Winds, other than the usual canyon breezes, are generated and give relative immunity to frost at exposed places, whenever a strong area of high barometric pressure moves inland from off the northern California coast or develops over the plateau region. Fontana, which lies just southwest of a large mountain pass, is periodically subject to winds of this nature.

An introduction to the Redlands district would not be complete unless accompanied by a more detailed description of Cajon Pass. The meteorological importance of this topographical landmark is due to the prominent control it exerts over southern California weather; more specifically, to understand the main forecasting problem in the Redlands district, it is first necessary to understand the mechanics of the canyon winds. In his paper¹ "Desert Wind in Southern California", Floyd D. Young deals with the subject thoroughly:

The air moving outward from the plateau high-pressure area is blocked on the south by the San Gabriel and San Bernardino Mountains. Wherever there is a break in these southern chains, such as Cajon Pass, the desert air streams through it and out onto the Great Valley of southern California. If the pressure difference between Nevada and southern California is only moderate, the desert winds usually are confined to rather narrow belts extending from the mouths of the passes to the ocean by the lowest and least obstructed route. * * *

Cajon Pass lies between the San Gabriel and San Bernardino Mountain Ranges, extending roughly north and south, turning toward the southeast near its southern extremity. It is a V-shaped notch about 17 miles long and quite narrow, extending from the Mojave Desert on the north to the Great Valley of southern California on the south. The slope from the summit of the pass northeastward is gradual, the summit being only slightly higher than the general level of the desert. The fall from the summit toward the

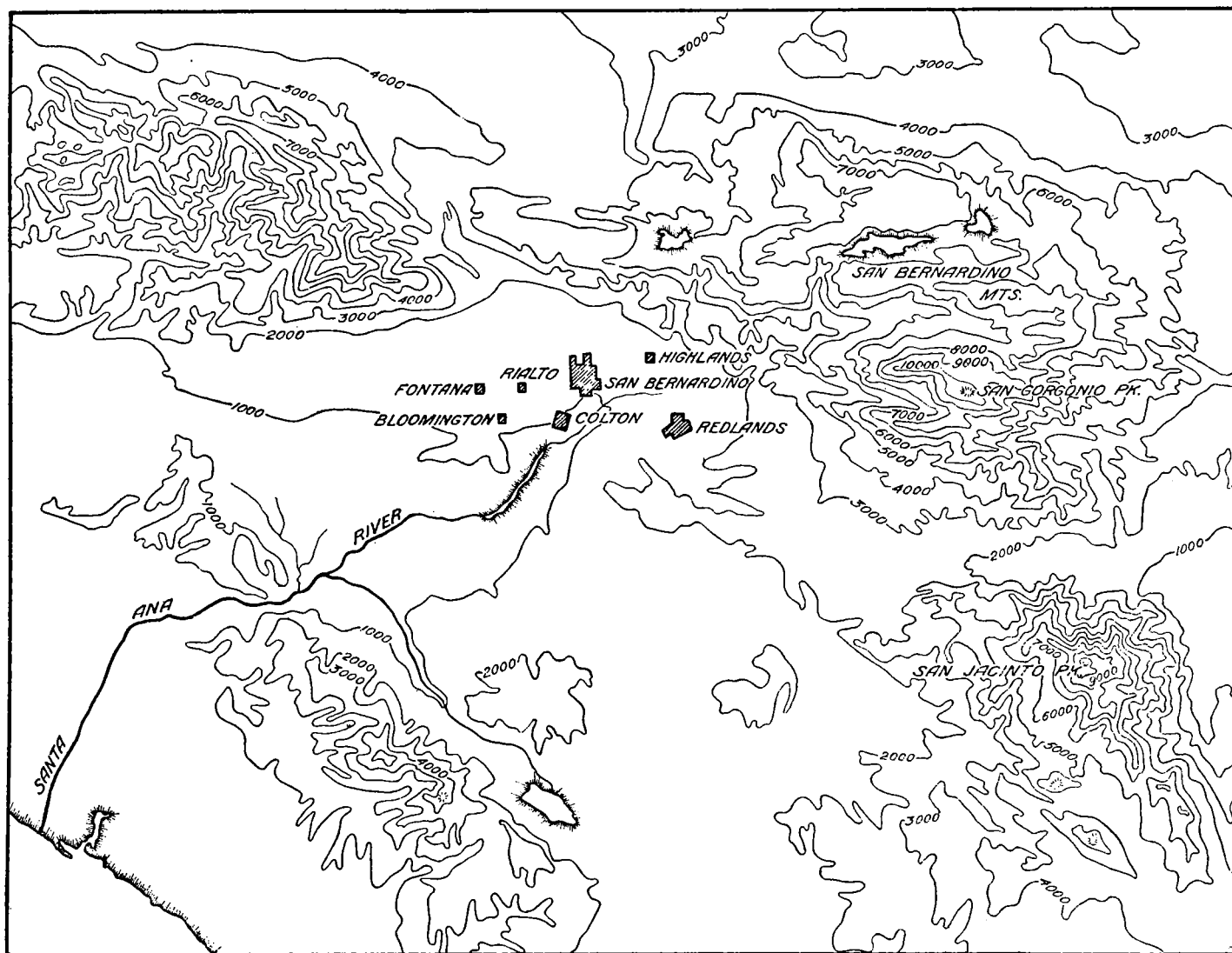
¹ *MONTHLY WEATHER REVIEW*, 59: 380-381, October 1931.

south is more abrupt, averaging about 115 feet to the mile. The approach to the pass from the desert side is shaped like a great horizontal V, with the sides formed by the mountains, which converge at the entrance. * * *

Desert winds from Cajon Pass usually maintain their identity in a remarkable manner. They move out over the valley floor, swing toward the southwest, and either follow the canyon of the Santa Ana River through the Santa Ana Mountains or move directly over the low mountains south of the canyon and then follow a well-defined path over the almost level plains of Orange County, reaching the ocean in the vicinity of Newport. On going eastward in the open country some 7 miles south of Cajon Pass, with light to gentle variable winds, one passes abruptly into an air stream moving from the north-northeast at a velocity of 30 to 35 miles per hour. The easterly limits of the stream are just as well marked, and one passes from a near gale into a region of relative calm within the space of half a mile. The width of the air stream under these conditions

due to north wind the minimum temperature at the Fontana key station, only 12 miles away, was 54°. Starting December 14, firing to protect oranges at Redlands was necessary on six consecutive mornings; but for the same period the average minimum temperature at Fontana was 52.7°.

There were 46 cold nights during the 1935-36 frost season (cold night defined as one when some station in the district reports freezing temperature); and in 29 instances the minimum temperature at Fontana was as low or lower than at Redlands. In a few cases Fontana was as much as 5° colder than Redlands, but in all these cases north wind was conspicuously absent on the preceding afternoon. Either the evening charts showed



probably will average about 5 miles. * * * The stream may shift its position slightly from time to time but appears to change but little in width or velocity.

In the winter months the same factors generating desert wind in southern California bring frost to protected locations. It is only as the wind ceases that exposed stations experience freezing temperatures. This is particularly true for Fontana, where often after a windy period, and with minimum temperatures rising elsewhere, it will experience a separate "little freeze" of its own.

On the morning of December 17, 1935, the minimum temperature at the Redlands key station was 25°; but

light variable wind or calm at Fontana, or else the pressure distribution favored the cessation of north wind before morning. Classifying wind by direction, the following distribution was obtained: Wind with southerly component, 14; due west, 4; wind with northerly component, 6; due east, 2; and calm, 3. The case for Fontana being colder than Redlands in the absence of north wind at Fontana rests upon these figures.

The wide range for minimum temperatures within a relatively short distance is due mostly to wind mixing the upper air with the colder surface air. The higher the afternoon temperature the greater will be the tempera-

ture inversion during the night and the greater will be the effect of night winds. From the description of the conditions under which Fontana is as cold or colder than Redlands, it follows that whenever strong wind is blowing the temperature differences between the two stations will be dependent upon the degree of thermal stratification of air near the ground. For purposes of illustration three mornings have been selected when the minimum temperature at Redlands was 25° and wind centered at Fontana. The minimum temperatures at Fontana vary directly as the maximum temperatures observed at Redlands for the preceding afternoons (table 1).

On freeze nights with low (43°–47°) afternoon temperature, there is little temperature inversion, and wind will affect the temperature relatively little. Growers claim that during the 1913 freeze there was no temperature inversion and that temperatures as low as 15° were accompanied by winds strong enough to extinguish heaters.

TABLE 1.—Minimum temperatures, °F., at Fontana, Calif., due to wind and temperature inversion

Date	Minimum temperature		Preceding maximum temperature, Redlands
	Redlands	Fontana	
Dec. 17, 1935.....	24.7	53.8	70.4
Jan. 18, 1936.....	25.1	46.2	63.0
Feb. 10, 1933.....	25.2	34.8	55.4

In fruit-frost work no attempt is made to forecast numerical values for temperatures above 32°. Growers are concerned only when damaging temperatures are imminent, and 32° constitutes a "safe temperature" for citrus fruits. The foregoing temperature correlation table would appear to be of only nominal forecasting value because the prerequisite conditions for freezing temperature and wind develop only at infrequent intervals. A very important application to the estimation of temperatures within the wind belt is possible, however, when forecasting for marginal wind stations such as Colton.

Colton lies 5 miles southeast of Fontana. It presents by far the most perplexing problem in forecasting minimum temperature. There is neither a minimum temperature formula² available to assist in forecasting, nor a dependable desert wind flow; it is subject to intermittent breezes; the difference in minimum temperatures on consecutive mornings is often large and unexpected.

The minimum temperature at Colton usually lies somewhere between that at Redlands and that at Fontana, sometimes more nearly the latter and at other times close to the minimum at Redlands. In the absence of north wind, when Fontana is likely to be the coldest station in the district, the minimum temperature forecast for Colton is guided by the temperature expected at Fontana; but whenever north wind is blowing it is necessary to consider temperatures both within and outside the wind belt.

When pressure gradients are large, the wind at Fontana spreads out and covers the whole western sector of which Colton is a part, with resulting temperatures above freezing over the entire windy area. When the wind is just beginning or ending, or is restricted to its usual narrow path, Colton experiences intermittent wind, during lulls in which the temperature falls with astonishing rapidity. The final minimum will be somewhere between the lowest

temperature in protected localities, such as Redlands, and the highest temperature within the center of the wind stream. Obviously it is much simpler to forecast minimum temperature for a station when the expected range is 25°–35° than when it is 25°–54°. If the wind at the marginal station is expected to produce only one-third the effect within the wind belt, a forecast of 28° will be issued for the first station, and an "above freezing" forecast (35°) for the second.

Paralleling somewhat the case of marginal wind is that of short-lived wind. Many times during a season wind will spring up locally in a district and die away just as suddenly, usually because of topographical differences between neighboring points or eddies from winds aloft. The duration and time of occurrence become very important considerations, for frost may precede or follow the wind.

If the wind is of short duration and occurs early in the evening, the temperature may still reach the value indicated by formula. The effect of short-lived winds is to break down surface temperature inversion and apparently³ arrest nocturnal cooling; but the effective radiating temperature of the surface air layer is raised so that, when the wind ceases, cooling proceeds at a faster rate than prior to the wind. The final minimum temperature will depend on the soil temperature which ultimately should drop to its usual value, wind notwithstanding, due to the small penetration of the outer thermal changes into the lower soil.

However, if the conditions of wind alter late in the period, a complicated thermal condition results. The temperatures will be lower or higher than those prior to the wind action, and the occurrence or nonoccurrence of frost will be determined by the none-too-dependable breezes. Conservative practice is, after accurately gaging the minimum temperature at the coldest location, to issue equal or slightly higher forecast values of temperature for the wind-exposed places, according to the degree of wind expected.

The conditions which presage other than cyclonic winds in the Redlands district depend upon a strong area of high barometric pressure moving in, or developing over, the plateau region, or upon a deepening of low pressure over southern California. If both conditions occur simultaneously, then for a given pressure gradient between the two regions maximum wind results. Conversely, if the high pressure over the plateau disintegrates, or the pressure over southern California rises, the probability of wind decreases with the destruction of wind gradients.

In the discussion which follows, hard and fast rules for forecasting minimum temperatures as affected by wind have been deliberately avoided. It is evident that gentle breezes on nights with large temperature inversions may prevent the radiational fall to as great an extent as strong wind on nights with only small temperature inversion. The method used in forecasting minimum temperature for the Redlands district stresses, first, forecasting the occurrence of wind, and then the departures from lowest temperature in protected locations, according to the type of temperature inversion indicated by the maximum temperature.

The technique used in forecasting wind is based upon a study of critical values of pressure gradients between certain significant stations, and the attending 24-hour pressure changes. Under certain conditions either set of

² It should be understood that only for the main key station in a district is it practical to take psychrometric observations, and on them base an empirically determined, minimum temperature formula; for sectional key stations other than the main key station, modifications of the estimate by formula are necessary and depend upon known topographical differences and a rational analysis of the current weather map.

³ "According to observations made by A. Ångström in California, with the ground 5° C. below air temperature the radiation emitted from the ground is reduced to about 93 percent of that of a black body at air temperature and the resultant outflow of radiation is reduced from 32 percent to 25 percent."—Meteorological Glossary, Second edition, p. 13.

data may singly indicate wind; but to cover all conditions favoring wind the two sets should be considered simultaneously.

By critical value of pressure gradient is meant the usual observed pressure difference between two significant stations when the wind is sufficiently strong in a sector to maintain temperatures above freezing. By observation it has been determined that whenever the pressure gradient between Tonopah and Los Angeles is 0.16 inch or more, Fontana will usually experience wind all night. When the Tonopah-Los Angeles pressure gradient is 0.20 inch, adjoining stations such as Bloomington and Rialto will usually share the wind with Fontana. In addition, when the Fresno-Los Angeles gradient is 0.16 or more, Colton, the marginal wind station, will also benefit from wind. But there still remain the nights like December 12, 1935 (see table 2), when the pressure gradient is less than the critical value, even negative, yet strong wind will blow somewhere in the district, thereby illustrating the fallacy of attempting to forecast wind by pressure gradients alone.

The 24-hour pressure change is used because station reports are received but once daily in the fruit-frost districts. It is conjectural whether the use of 12-hour pressure changes would be an improvement over this method, since the 24-hour changes are regarded as being more representative of the major changes in air mass that lead to wind in a district. Moderate changes in pressure over a 24-hour period reveal a definite tendency which may be logically projected into the next 16-hour forecast period; but the 12-hour pressure change may be less indicative.

In the 1935-36 season there were 18 nights with wind blowing somewhere in the Redlands district. Where the

temperatures differ widely at the sectional key stations, the difference is due to wind. Table 2 lists chronologically these windy nights, giving the essential pressure data and temperatures. The type of wind, the path of wind, and the width of the belt may be inferred from an inspection of temperatures, except in the cases where additional information is provided in the notes. The sectional key stations are arranged in an east-to-west sequence, the band being approximately 12 miles long by 5 miles wide. The wind enters from a point on the northern border and usually is confined to a narrow path in crossing the strip.

Probably the most striking case during the season was following the night of January 16, when the wind reversed its usual habit and centered near Highland and Redlands, practically no wind being observed in the western sector. The conditions leading to this wind were the significant pressure gradient between Fresno and Los Angeles, and the large divergent pressure changes occurring simultaneously on the plateau and in southern California.

Other similar examples are the nights of December 8, 12, 18, and 31, and January 11. In nearly all these cases wind was experienced in Redlands shortly after midnight, but the main flow was centered in the western sector. Invariably with large Fresno-Los Angeles pressure gradient, and negative Tonopah-Los Angeles gradient, the wind as it issues from Cajon Pass will not experience its customary deflection toward the southwest and Fontana. It is only as the Tonopah-Los Angeles pressure gradient increases, and the Fresno-Los Angeles gradient decreases, that the wind can resume its normal path toward the sea, which predicates that the center of high pressure lies on the plateau rather than off the northern California coast.

TABLE 2.—Wind data, 1935-36 frost season, Redlands, Calif.

Date	24-hour pressure change (first line) and pressure gradients (second line)						Maximum temperature, Redlands, Calif.	Minimum temperatures for the following morning at sectional key stations						Notes
	Los Angeles	Tonopah	Fresno	Winnemucca	Needles	Yuma		Redlands	Highland	Colton	Rialto	Bloomington	Fontana	
1935														
Nov. 14	+ .14	+ .22	+ .08	+ .04	+ .30	+ .28	74	29	33	37	38	38	42	Wind 2 a. m., 6 a. m. in Redlands. Wind after 12:30 a. m. in all sectors.
Dec. 8	+ .18	+ .02	+ .12	+ .04	+ .18	+ .20								
Dec. 12	+ .12	+ .08	+ .10	+ .12	+ .32	+ .22	65	39	Above freezing					
Dec. 13	+ .04	+ .38	+ .12	+ .36	+ .28	+ .20	62	35	34	47	53	52		
Dec. 14	+ .08	+ .28	+ .20	+ .06	+ .08	+ .04	70	28					29	
Dec. 15	0	+ .10	+ .02	+ .14	+ .12	+ .12	67	26	28	31	46	41	49	
Dec. 16	+ .04	+ .30	+ .14	+ .10	+ .12	+ .08	68	26	26	27	38	33	52	
Dec. 17	+ .06	+ .18	+ .14	+ .14	+ .04	+ .06	70	26	27	30	43	41	54	
Dec. 18	+ .04	+ .22	+ .04	+ .12	+ .12	+ .06	71	29	33	29	38	32	55	{ Wind in Highland and Rialto after 1 a. m. Redlands after 4 a. m.
Dec. 31	+ .02	+ .26	+ .12	+ .20	+ .10	+ .06	65	34	Above freezing				Wind after 1 a. m. in Redlands.	
1936														
Jan. 11	+ .04	+ .02	+ .18	+ .22	+ .14	+ .04	63	34	34	34	33	36	49	{ Wind in Highland all night. Wind in Redlands beginning 12:45 a. m. Average temperature thereafter, 40°.
Jan. 16	+ .12	+ .06	+ .08	+ .16	+ .24	+ .20	59	30	41	32	31	32	30	
Jan. 17	+ .02	+ .26	+ .02	+ .26	+ .18	+ .12	68	25	30	40	46	48	46	
Jan. 19	+ .12	+ .06	+ .04	+ .04	+ .10	+ .10	74	30	30	34	33	37	52	{ Wind path cut through Rialto town. Key station was 33°. Other survey stations only a few blocks away were above 40°.
Jan. 20	+ .02	+ .18	+ .20	+ .08	+ .10	+ .06	75	33	32	38	45	38	55	
Jan. 21	+ .10	+ .22	+ .10	+ .14	+ .12	+ .08	77	31	30	32	34	35	55	
Jan. 22	+ .04	+ .08	+ .02	+ .08	+ .06	+ .06	76	34	32	35	32	38	58	
Jan. 29	+ .06	+ .38	+ .10	+ .24	+ .08	+ .08	62	32	33	38	53	55	53	

¹ Represents pressure gradient from Winnemucca to Tonopah. The others are referable to Los Angeles.

The force of the wind and the relative values of contributing pressure gradients determine where the wind will strike. Pairs of gradients indirectly represent isobar curvature and orientation; and by grouping combinations of significant gradients in pairs, an empirical method which discounts topographical configurations as a further modifying influence is afforded, subject to the condition that as the barometric gradients become steeper, the ability of mountains or passes to deflect becomes decreasingly effective with the increased wind. With pressure gradients between the plateau and southern California in excess of 0.45 inch, the mountains to the north of the Great Valley lose their effectiveness as barriers, and desert air flows over their tops. (See table 3.)

TABLE 3.—Wind path and significant pressure gradients

Date	Pressure gradients		Maximum temperature	Ensuing minimum temperature						
	Los Angeles-Fresno	Los Angeles-Tonopah		Red-lands	Red-lands	High-land	Col-ton	Rialto	Bloom-ington	Fon-tana
Jan. 16, 1936.....	+0.20	-0.06	59	30	41	32	31	31	30	30
Jan. 17, 1936.....	+0.20	+0.22	63	25	30	40	46	48	46	46
Dec. 17, 1935.....	+0.04	+0.22	70	26	27	30	43	46	46	54

¹ Wind after 1 a. m.; average temperature thereafter 40°. Bold-face figures show where wind centered.

Rates of pressure change at significant stations are important considerations. A difference in rate between two regions represents a resultant effect free to produce or maintain wind. If the pressure builds up or decreases everywhere alike, the flow remains unchanged; when the rates of pressure change are different, the gradients become accentuated. From the study of pressure data,

it has been observed that any 24-hour pressure change at Tonopah greater than twice the magnitude of the 24-hour pressure change at Los Angeles is favorable for producing wind.

How the rates of pressure change may be the basis for wind forecasts is best demonstrated by reference to the nights of December 15, 16, and 17 in table 2. The evening of December 16 showed a moderate increase in the Tonopah-Los Angeles pressure gradient, but only a slight decrease in the Fresno-Los Angeles gradient. The 24-hour pressure change showed rates at Tonopah and Los Angeles in about a 2:1 ratio. In the table, opposite December 16 but for the morning of the 17th, Rialto minimum temperature has dropped to 35°; if the wind had continued to abate in that locality, freezing temperature should logically have been expected there and at Colton the following morning. On the evening of December 17, both the Tonopah-Los Angeles and Fresno-Los Angeles pressure gradients showed decided drops, but the wind increased at all locations, including Colton. The only apparent explanation is the difference in rates of pressure change. The 24-hour change at Tonopah over Los Angeles was in the ratio of 3:1.

It is understood, of course, that the principles enumerated herein only partly cover the problem. In some years pressure on the plateau runs consistently high merely because of the hypothetical reduction to sea level; at other times the vertical structure of the air over the Great Valley determines whether the wind will blow along the surface or merely through the tops of the tallest wind-break trees. In the first case, a given pressure gradient between the plateau and southern California produces a minimum amount of wind; and, in the second case, additional considerations preclude exact analysis of impending minimum temperature. Wind seldom, if ever, completely conforms with expectation. This paper can only represent an attempt to circumvent certain frost-forecasting difficulties encountered in the field.

TROPICAL DISTURBANCE, OCTOBER 9-10, 1936

By I. R. TANNEHILL

[Marine Division, Weather Bureau, Washington, November 1936]

Only one tropical disturbance was reported during October from the North Atlantic Ocean (including the Gulf of Mexico and Caribbean Sea); this disturbance was of slight intensity; it was in evidence on October 9 and 10 on the west coast of Yucatan and in the Bay of Campeche.

The initial stages of the disturbance are described in the report of W. R. Stevens, forecaster on duty at New Orleans, as follows:

For a few days previous to October 9, conditions had been unsettled over the northwest Caribbean Sea, attended by slowly falling pressure over the Yucatan Peninsula. Heavy rains were reported on the morning of October 9 at Payo Obispo and Cozumel Island. The 8 p. m. map of October 9 showed a definite circulation over the Gulf of Campeche and the pressure at Merida had fallen to 29.70 inches, representing a 24-hour pressure fall of 0.08 inch, while pressure had risen slightly on the east coast of the Yucatan

Peninsula. The reports at hand indicated that the disturbance was just forming and was probably central near Campeche.

Observations from the vicinity of the disturbance are inadequate to determine the exact course of the center; it appears to have moved south-southwestward across the Bay of Campeche and inland a short distance east of Frontera on October 10. The situation on the morning of the 11th, when the disturbance was centered north of Tapachula, is shown on chart IX.

Advisory information regarding the disturbance was disseminated on the 9th and 10th from the New Orleans forecast center.

An account of tropical disturbances which occurred during October in the Pacific Ocean near Mexico will be found on page 343.